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COHERENT PHASE COMPENSATION METHOD BASED ON DIRECT IF SAMPLING IN WIDEBAND RADAR

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Abstract—In order to eliminate the negative influence of the rotational phase component (RPC) of target prominent scattering centres on the performance of Doppler centroid tracking (DCT) method, a coherent phase compensation method is proposed. The coherence of echo pulses sampled directly in intermediate frequency (IF) is firstly analyzed and proved. Based on the coherence property, the proposed approach improves the translational phase component (TPC) estimation accuracy of DCT. Compared to the modified Doppler centroid tracking (MDCT) algorithm, the proposed method achieves better phase compensation performance with simpler operations. Both the theoretical analysis and experimental results based on the real ISAR data prove the effectiveness and efficiency of the presented strategy.

1. INTRODUCTION

The inverse synthetic aperture radar (ISAR) can obtain high resolution images of moving targets by utilizing the information inherent in differential target Doppler and is greatly contributive in target recognition [1–6]. Generally, ISAR aims at non-cooperative moving target, whose motion can be decomposed into rotational motion and translational motion. The rotational motion is beneficial to ISAR imaging whereas the existence of translational motion deteriorates the performance and must be accurately determined and compensated [7, 8]. Therefore, translational motion compensation is the fundamental requirement in ISAR imaging, which can usually be

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carried out by two steps: envelop alignment and phase compensation. ISAR imaging raises a high demand on phase compensation. Thus, improving the precision of phase compensation plays an important role in improving the quality of ISAR image. So far, there have been lots of research works focusing on phase compensation, the research directions of which generally fall into two categories: parametric methods and non-parametric methods [9–12]. Among these numerous methods, Doppler centroid tracking (DCT) [13–15] algorithm is one of the state-of-the-art methods. DCT algorithm is the optimal one based on maximum likelihood criterion and can reduce the tracking loss caused by scintillation and obscuring while tracking the whole object instead of whichever scattering point [14]. It also has less computation load and is feasible to real-time imaging. However, the DCT algorithm has poor translational phase component (TPC) estimation accuracy because of the rotational phase component (RPC) of target prominent scattering centres. The modified Doppler centroid tracking (MDCT) [15] algorithm can eliminate the effect of the RPC on the estimation of the TPC, but the computational complexity caused by multi-time iteration makes the MDCT method hard to be applied in real systems.

With the development of analog-to-digital converter (ADC), direct intermediate frequency (IF) sampling for wideband radar becomes realistic and is widely employed in engineering [16]. Compared to STRETCH processing [17, 18], direct IF sampling raises a high demand on sampling frequency. It also brings obvious advantages, one of which is the coherence of echo pulses. By adopting this coherent property, a coherent phase compensation method is developed in this paper, which eliminates the negative influence of the RPC on the estimation accuracy of the TPC and improves the quality of ISAR image with simpler operations.

The remainder of this paper is organized as follows. In Section 2, the DCT algorithm is briefly introduced, as well as its limitation. Further, we analyzed the coherence of echo pulses sampled directly in IF, and place an emphasis on coherent phase compensation method in Section 3. Experimental results and performance analysis are reported in Section 4 and Section 5 concludes the paper.

2. DCT ALGORITHM AND ITS LIMITATION

DCT algorithm is the embodiment of target centroid tracking method first proposed by Prickett [19]. It tracks the target centroid and forces the average Doppler to be zero. Its concrete implementation steps can be described as follows: After envelope alignment, the weighted mean of the complex exponential function of adjacent echo phase difference on weighted amplitude is calculated. In other words, the complex exponential function of Doppler centroid phase difference is obtained as follows [15]:

$$\exp\left[j\Delta\zeta(m)\right] = \sum_{n=1}^{N} s_{m,n}^{*} s_{m+1,n} \Bigg/ \left|\sum_{n=1}^{N} s_{m,n}^{*} s_{m+1,n}\right| \tag{1}$$

where $m = 1, 2, \ldots$ is the frame number, $s_{m,n}$ and $s_{m+1,n}$ are the sub-echoes of range cell n in the adjacent echoes (Frame m and Frame $m+1$), $\Delta\zeta(m)$ stands for the TPC induced by envelope motion. The phase compensation is accomplished by calibrating the phase of all range cells via this function.

However, the RPC of target motion may reduce the TPC estimation accuracy and deteriorates the compensation performance of DCT method mentioned above. In [15], based on circular shifting, windowing and iteration steps, the authors proposed the MDCT method which applies the phase gradient autofocus (PGA) [20, 21] algorithm to solve this problem. Unfortunately, it needs 8 to 10 times of iteration to achieve good compensation performance, which result in huge computation load and make this method hard to be applied in real systems.

3. PHASE COMPENSATION METHOD BASED ON THE COHERENCE OF ECHO PULSES

Most of modern radars utilize not only the amplitude, but also the phase and frequency information for their main functions. Thus, radar coherence plays a more and more important role in the system performance. However, the coherence of echo pulses is usually destroyed in STRETCH processing. With the development of ADC, ultra-high speed direct IF sampling for wideband radar is no longer an inextricable problem and is employed widely in engineering. Direct IF sampling is the precondition for maintaining the coherence in pulse compression radar.

3.1. Coherence of Direct IF Sampling

The linear frequency modulation (LFM) signal transmitted by radar can be expressed as

$$s(t) = \mathrm{rect}\left(\frac{t}{T_t}\right) \exp\left[j2\pi\left(f_c t + \frac{1}{2}\gamma t^2\right)\right] \tag{2}$$

where T_t is the pulse duration, f_c the carrier frequency, t time variable, and γ the chirp rate. It is assumed that the amplitude of the LFM signal is 1 for the convenience of analyzing. Using R_i as the distance between the target and radar, the target echo return $s_r(t)$ can be written as

$$s_r(t)=\mathrm{rect}\left(\frac{t-2R_i/c}{T_t}\right)\exp\left\{j2\pi\left[f_c\left(t-\frac{2R_i}{c}\right)+\frac{1}{2}\gamma\left(t-\frac{2R_i}{c}\right)^2\right]\right\} \tag{3}$$

where c is the velocity of light. After mixing processing, the echo return is converted down to IF signal $s_I(t)$.

$$\begin{aligned}&s_I(t)\\&=\mathrm{rect}\left(\frac{t-2R_i/c}{T_t}\right)\exp(-j4\pi f_cR_i/c)\exp\left\{j2\pi\left[f_It+\frac{1}{2}\gamma(t-2R_i/c)^2\right]\right\}\end{aligned} \tag{4}$$

where f_I stands for the centre frequency of IF echo signal. Then the baseband signal $s_B(t)$ can be written as

$$s_B(t)=\mathrm{rect}\left(\frac{t-2R_i/c}{T_t}\right)\exp(-j4\pi f_cR_i/c)\exp\left[j\pi\gamma(t-2R_i/c)^2\right] \tag{5}$$

According to the stationary phase principle, we obtain the frequency domain expression of $s_B(t)$ from (5).

$$\begin{aligned}&S_B(\omega)\\&=\frac{1}{\sqrt{\gamma}}\mathrm{rect}\left(\frac{\omega}{2\pi\gamma T_t}\right)\exp\left[j\left(-\frac{\omega^2}{4\pi\gamma}+\frac{\pi}{4}\right)\right]\exp\left(-j\frac{2R_i\omega}{c}\right)\exp\left(-j\frac{4\pi f_cR_i}{c}\right)\end{aligned} \tag{6}$$

The matched filter of signal expressed by (6) can be written as

$$H(\omega)=\frac{1}{\sqrt{\gamma}}\mathrm{rect}\left(\frac{\omega}{2\pi\gamma T_t}\right)\exp\left[-j\left(-\frac{\omega^2}{4\pi\gamma}+\frac{\pi}{4}\right)\right] \tag{7}$$

So the output signal of the matched filter can be expressed as

$$\begin{aligned}&s_p(t)\\&=s_B(t)*h(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}S_B(\omega)H(\omega)\exp(j\omega t)d\omega\\&=\frac{1}{2\pi\gamma}\exp\left(-j\frac{4\pi f_cR_i}{c}\right)\int_{-\infty}^{+\infty}\mathrm{rect}\left(\frac{\omega}{2\pi\gamma T_t}\right)\exp\left(-j\frac{2R_i\omega}{c}\right)\exp(j\omega t)d\omega\\&=\frac{T_t}{2}\exp\left(-j\frac{4\pi f_cR_i}{c}\right)\mathrm{sinc}\left[\pi\gamma T_t\left(t-\frac{2R_i}{c}\right)\right]\end{aligned} \tag{8}$$

We can see from (8) that the phase of signal after matched filtering is

$$\phi_d=-4\pi f_cR_i/c \tag{9}$$

In (9), ϕ_d is related to R_i only and changes when changes take place in R_i. That means the echo phase keeps a strict and stable relationship with the phase of transmitted signal. In other words, the echo pulses are coherent.

For STRETCH processing, the target echo signal can be expressed in frequency domain as [22]:

$$\begin{aligned} S_p(f_i) \;=\; & T_t \mathrm{sinc}\left[T_t\left(f_i + 2\frac{\gamma}{c}R_\Delta\right)\right]\exp(-j4\pi f_c R_\Delta/c) \\ & \exp\left[-j4\pi f_i R_\Delta/c\right]\exp\left(j4\pi\gamma R_\Delta^2/c^2\right) \end{aligned} \tag{10}$$

where $R_\Delta = R_i - R_{\mathrm{ref}}$, R_{ref} is the reference distance. The second exponential term in (10) is residual video phase (RVP) term, and the third exponential term is the envelop "sideling" term when $R_\Delta \neq 0$. This two exponential phase term can be eliminated by phase compensation at the envelope peak point where $f_i = -2\frac{\gamma}{c}R_\Delta$ [17]. The first phase term is the echo phase brought by translational motion:

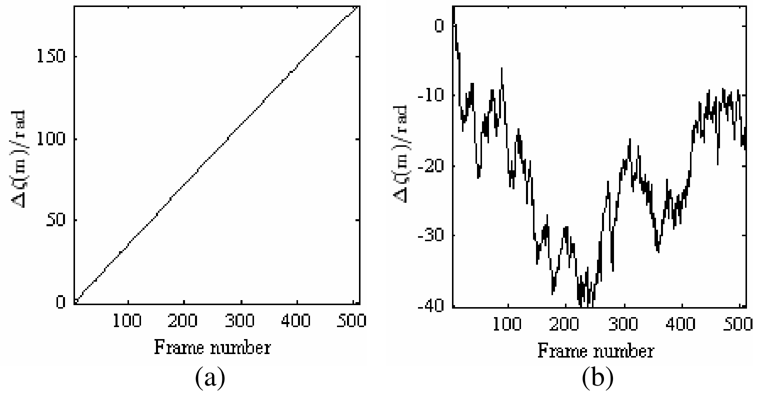
$$\phi'_d = -4\pi f_c R_\Delta/c = -\frac{4\pi}{c}f_c(R_i - R_{\mathrm{ref}}) \tag{11}$$

As shown in (11), the phase of STRETCH processing echo pulse is related to the radial distance R_i of target and the reference distance R_{ref}. R_{ref} is closely related to the time-delay of the narrowband echo, which is not precise enough. Thus, the phase term in (11) can not be obtained precisely and finally induces the incoherence of echo returns of STRETCH processing.

3.2. Coherent Phase Compensation Method

Equation (8) shows that, for the 1-D range profile of matched filtering based on direct IF sampling, phase compensation means to eliminate the exponential term $\exp(-j4\pi f_c R_i/c)$ which truly reflects the phase variation induced by translational motion of the target. Even though there may be accelerated motion during observation, the phase transformation curve caused by motion should be continuous and smooth because of the inertial of the target. The non-ideal factors such as system distortion and radio propagation path can just superimpose little ripple on the smooth curve. STRETCH processing destroys the coherence of echo pulses and does not have this property. By employing DCT method, Fig. 1 shows the phase difference curves of adjacent echo pulses achieved by direct IF sampling and STRETCH processing respectively in a phased array radar.

We can see from Fig. 1(a) that the phase difference curve of adjacent return echoes sampled directly in IF is continuous and approximately smooth. The little ripple is induced by the non-ideal



(a)

(b)

Figure 1. Phase difference curves of adjacent echo pulses achieved by direct IF sampling and STRETCH processing. (a) Direct IF sampling. (b) STRETCH processing.

factors such as system distortion and radio propagation path. Also we can find from the figure that the phase difference has an increasing trend which indicates the accelerated motion of the target. For the return echoes received by STRETCH processing, its phase difference curve shown in Fig. 1(b) undulates tempestuously and cannot reflect the motion states of the target. This is due to the coherence destroying by STRETCH processing. Based on the coherence of direct IF sampling, we can smooth the phase difference curve and eliminate the phase error using the least squares curve fitting method. Then we achieve the accurate phase difference curve and can improve the phase compensation effect.

The concrete steps of the algorithm are shown bellow.

1. Achieving the complex exponential function of Doppler centroid phase difference shown in (1) using DCT method, so we can obtain the phase difference curve of adjacent return echoes (curve of $\Delta\zeta(m)$);
2. Implementing the curve fitting using the least squares curve fitting method, we obtain the accurate phase difference function $\Delta\zeta'(m)$;
3. Reconstruct the phase compensation exponential function $C(m)$ using $\Delta\zeta'(m)$. $C(m)$ can be expressed as

$$C(m) = \exp\left(j\sum_{m=1}^{m-1}\Delta\zeta'(m)\right) \tag{12}$$

4. Accomplish the phase compensation by multiplying the 1-D range profile data with the corresponding $C(m)$.

As can be seen from the steps above, the algorithm proposed in this paper is on the basis of DCT method, and improves the TPC estimation accuracy using only one time of curve fitting. In Step 2, it is important to choose a proper polynomial order when using curve fitting. Numerous experiments show that, in order to reflect the actual phase changes induced by motion of the targets as much as possible, the polynomial order should be set to 3.

4. EXPERIMENTAL VERIFICATION AND ANALYSIS

4.1. Algorithm Verification

In order to verify the algorithm presented above, the performance of phase compensation employing the proposed method is compared with that of unmodified DCT method in this section. Aircraft echo data sampled by experimental phased array radar is adopted. Fig. 2 shows the phase difference curve after curve fitting using the least squares curve fitting method, while Fig. 3 shows the difference between pre- and post curve fitting. As shown in Fig. 2, the phase difference curve tallies with the motion states of the target. Meanwhile, curve in Fig. 3 indicates that there are errors between the phase estimated by DCT method and that induced by target motion. The difference, which is just the negative influences of the RPC and other system factors on the TPC estimation accuracy, lies within the scope of ±0.6 radian. ISAR imaging is processed after phase compensation which uses the phase difference function achieved by the least squares curve fitting method. Fig. 4(a) shows the ISAR imaging results obtained by using unmodified DCT method, while Fig. 4(b) are the ISAR images obtained by adopting the MDCT method and Fig. 4(c) via the coherent

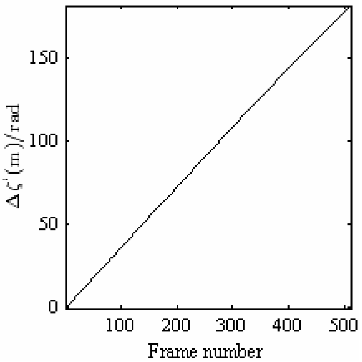


Figure 2. Post fitting phase difference curve.

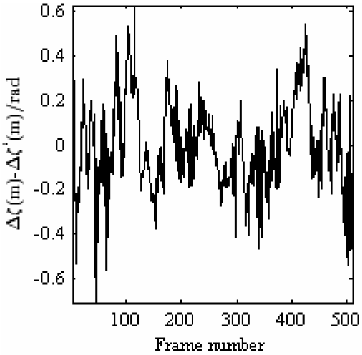
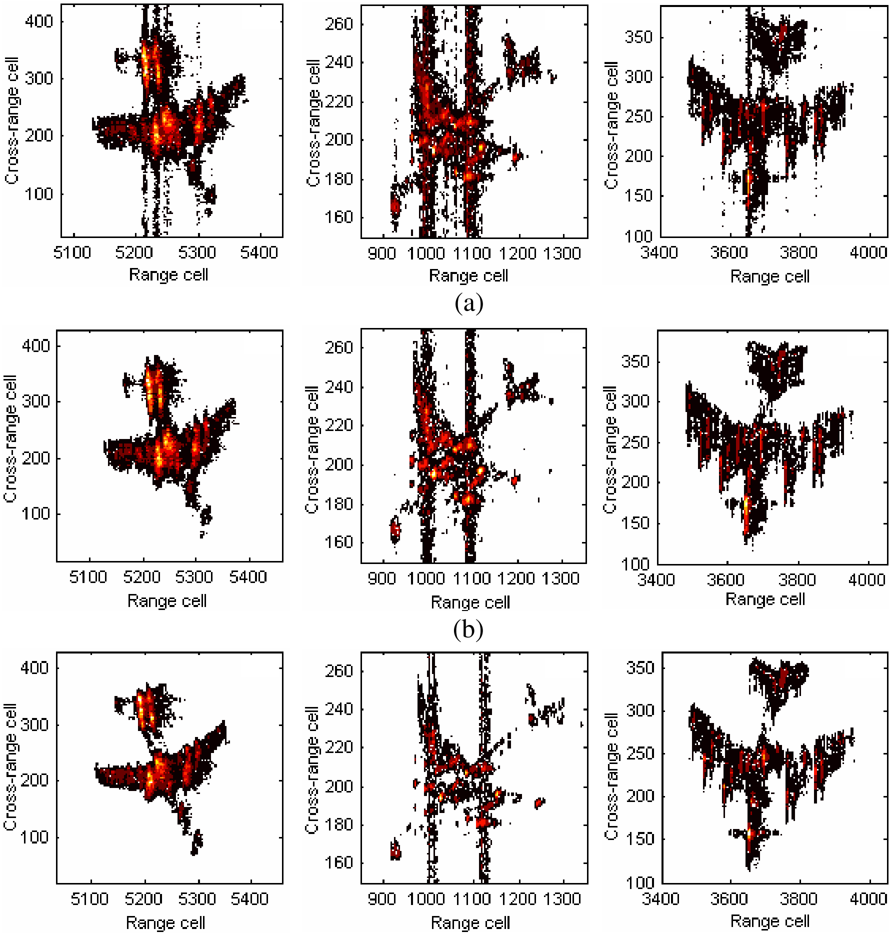


Figure 3. Difference between pre- and post fitting.



(a)

(b)

(c)

Figure 4. ISAR imaging results via unmodified (a) DCT method, (b) MDCT method and (c) method presented in this paper.

phase compensation algorithm proposed in this paper. It can be seen from the figures that, the image focusing quality of Fig. 4(c) are better than that of Fig. 4(a) and Fig. 4(b). Thus the method proposed in this paper is effective.

4.2. Performance Analysis

The performance of phase compensation directly affects the quality of ISAR image which can be quantitatively evaluated by image entropy [23–25]. Therefore, image entropy is adopted for the

Table 1. The ISAR image entropy of Fig. 4.

Phase compensation method	ISAR image entropy		
	(1)	(2)	(3)
Unmodified DCT method (Fig. 4(a))	8.7392	9.3252	7.8441
MDCT method (Fig. 4(b))	8.6374	9.1817	7.7481
Method proposed in this paper (Fig. 4(c))	8.627	9.1485	7.1288

performance evaluation of phase compensation in this section. On the basis of the same algorithms for other processing (such as distortion compensation, envelope alignment, image reconstruction, et al.), the better phase compensation performance, the higher image quality and lower image entropy, and vice versa.

The ISAR image entropy of Fig. 4 are obtained and shown in Table 1. (Coherent envelope alignment method [26] and RD imaging method are adopted for envelope alignment and image reconstruction respectively.) As shown in Table 1, the ISAR images obtained by adopting the unmodified DCT method have the highest image entropy, while the ISAR images obtained by using the algorithm proposed in this paper have the lowest entropy. This indicates that the phase compensation method proposed in this paper has the best performance.

It is assumed that the frame count of echoes used for one ISAR image is M, and the sample number of one frame echo is N. According to the steps of MDCT algorithm described in [10], we can obtain the total computation load of the MDCT algorithm. That is $9(M-1)(8N+2M) + 34NM\log_2 M + 24NM$ times of multiplications with $9(M-1)(5N+1.5M-1) + 42.5NM\log_2 M + 16(NM-1)$ times of additions. In the same way, the total computation load of the method proposed in this paper is obtained, which is $(M-1)(8N+2M+42) + 2NM\log_2 M + 124$ times of multiplications with $(M-1)(5N+1.5M+21) + 2.5NM\log_2 M + 18$ times of additions. In Section 4.1, the sample number of one frame echo is 2.4×10^6. And 512 frames of echoes are used for one ISAR image. Then according to the analysis aforementioned, the computation loads of the MDCT method and strategy proposed in this paper are obtained and shown in Table 2. We can see from the table that the computation load of MDCT method is about 16 times as much as that of the method proposed in this paper.

In a word, compared with the MDCT method, our method improves the unmodified DCT method and achieves better performance of phase compensation with simpler operations.

Table 2. The computation loads of MDCT method and the method proposed in this paper (the approximate value).

Phase compensation method	multiplication (times)	addition (times)
MDCT method	4.94×10^{11}	5.45×10^{11}
Method proposed in this paper	3.19×10^{10}	3.38×10^{10}

5. CONCLUSIONS

The coherence plays a more and more important role in radar system performance. In this paper, the coherence of echo pulses sampled directly in IF is proved. The signal model of echo pulses is presented. And the mathematical formula for the coherence of echo pulses is derived. By comparing the phase difference curves of echo pulses sampled directly in IF with that of STRETCH processing, the validity of this theoretical analysis is confirmed. Based on the coherence property, a coherent phase compensation algorithm is proposed in this paper. Compared to MDCT method, the proposed algorithm improves the TPC estimation accuracy and achieves better ISAR image quality with less computation load. The experimental results based on the real ISAR data show that the proposed strategy is an effective and efficient phase compensation method.

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